Fundamental Principles of Theoretical Physics and Concepts of Quantum Protectorate and Emergence[1]

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Abstract

A concise survey of the advanced unifying ideas of modern physics, namely, spontaneous symmetry breaking, quasiaverages, quantum protectorate and emergence was presented. The interrelation of the concepts of symmetry breaking, quasiaverages and quantum protectorate was analyzed in the context of quantum theory and statistical physics. The main aim of this analysis was to demonstrate the connection and interrelation of these conceptual advances of the many-body physics and to try to show explicitly that those concepts, though different in details, have a certain common features. Some problems in the field of statistical physics of complex materials and systems e.g. foundation of the microscopic theory of magnetism and superconductivity were pointed in relation to these ideas.

The development of experimental techniques over the last decades opened the possibility for studies and investigations of a wide class of extremely complicated and multidisciplinary problems in physics, astrophysics, biology, material science, etc. In this regard theoretical physics is a kind of science which forms and elaborates the appropriate language for treating these problems on the firm ground [1]. This idea was expressed in the statement of F. Wilczek [2]: "primary goal of fundamental physics is to discover profound concepts that illuminate our understanding of nature". For example, the theory of symmetry is a basic tool for understanding and formulating the fundamental notions of physics. Many fundamental laws of physics in addition to their detailed features possess various symmetry properties. These symmetry properties lead to certain constraints and regularities on the possible properties of matter. Thus the principles of symmetry belongs to the underlying principles of physics. Moreover, the idea of symmetry is a useful and workable tool for many areas of quantum field theory, physics of elementary particles, statistical physics and condensed matter physics. Symmetry considerations show that symmetry arguments are very powerful tool for bringing order into the very complicated picture of the real world [2, 3, 4, 5, 6].
It is well known that there are many branches of physics and chemistry where phenomena

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The Conference is dedicated to the 100th anniversary of Professor Yakov Petrovich Terletsky (1912 - 1993), the famous theoretical physicist, founder of the Theoretical Physics Department at Peoples' Friendship University of Russia. He made an important contribution to Particle and Statistical Physics and the development of higher education in Russia.

occur which cannot be described in the framework of interactions amongst a few particles. As a rule, these phenomena arise essentially from the cooperative behavior of a large number of particles. Such many-body problems are of great interest not only because of the nature of phenomena themselves, but also because of the intrinsic difficulties in solving problems which involve interactions of many particles (in terms of known P.W. Anderson's statement: "more is different"). It is often difficult to formulate a fully consistent and adequate microscopic theory of complex cooperative phenomena. More recently it has been possible to make a step forward in solving of these problems. This step leads to a deeper understanding of the relations between microscopic dynamics and macroscopic behavior on the basis of emergence concept [6, 7, 8, 9, 10].

Emergence - macro-level effect from micro-level causes - is an important and profound interdisciplinary notion of modern science. There has been renewed interest in emergence within discussions of the behavior of complex systems [6, 7, 8, 9, 10, 11, 12]. A vast amount of current researches focuses on the search for the organizing principles responsible for emergent behavior in matter [6, 7, 8, 9, 10, 11, 12], with particular attention to correlated matter, the study of materials in which unexpectedly new classes of behavior emerge in response to the strong and competing interactions among their elementary constituents. As it was formulated by D.Pines [12]: "we call emergent behavior : the phenomena that owe their existence to interactions between many subunits, but whose existence cannot be deduced from a detailed knowledge of those subunits alone". There has been renewed interest in emergence within discussions of the behavior of complex systems and debates over the reconcilability of mental causation, intentionality, or consciousness with physicalism. This concept is also at the heart of the numerous discussions on the interrelation of the reductionism and functionalism.

In the search for a "theory of everything" [11], scientists scrutinize ever-smaller components of the universe. String theory postulates units so minuscule that researchers would not have the technology to detect them for decades. R.B. Laughlin [8, 9, 11], argued that smaller is not necessarily better. He proposes turning our attention instead to emerging properties of large agglomerations of matter. For instance, chaos theory has been all the rage of late with its speculations about the "butterfly effect," but understanding how individual streams of air combine to form a turbulent flow is almost impossible [13]. It may be easier and more efficient, says Laughlin, to study the turbulent flow. Laws and theories follow from collective behavior, not the other way around, and if one will try to analyze things too closely, he may not understand how they work on a macro level. In many cases, the whole exhibits properties that can not be explained by the behavior of its parts. As Laughlin points out, mankind use computers and internal combustion engines every day, but scientists do not totally understand why all of their parts work the way they do. R.B. Laughlin and D. Pines invented an idea of a quantum protectorate [8, 9, 11], "a stable state of matter, whose generic low-energy properties are determined by a higherorganizing principle and nothing else". This idea brings into physics the concept that emphasize the crucial role of low-energy and high-energy scales for treating the propertied of the substance [8, 9, 11, 12]. It is known that a many-particle system (e.g. electron gas) in the low-energy limit can be characterized by a small set of collective (or hydrodynamic) variables and equations of motion corresponding to these variables. Going beyond the framework of the low-energy region would require the consideration of plasmon excitations, effects of electron shell reconstructing, etc. The existence of two scales, low-energy and high-energy, in the description of physical phenomena

was used in physics, explicitly or implicitly. According to R. Laughlin and D. Pines,"The emergent physical phenomena regulated by higher organizing principles have a property, namely their insensitivity to microscopics, that is directly relevant to the broad question of what is knowable in the deepest sense of the term. The low energy excitation spectrum of a conventional superconductor, for example, is completely generic and is characterized by a handful of parameters that may be determined experimentally but cannot, in general, be computed from first principles. An even more trivial example is the low-energy excitation spectrum of a conventional crystalline insulator, which consists of transverse and longitudinal sound and nothing else, regardless of details. It is rather obvious that one does not need to prove the existence of sound in a solid, for it follows from the existence of elastic moduli at long length scales, which in turn follows from the spontaneous breaking of translational and rotational symmetry characteristic of the crystalline state. Conversely, one therefore learns little about the atomic structure of a crystalline solid by measuring its acoustics. The crystalline state is the simplest known example of a quantum protectorate, a stable state of matter whose generic low-energy properties are determined by a higher organizing principle and nothing else. Other important quantum protectorates include superfluidity in Bose liquids such as He4 and the newly discovered atomic condensates, superconductivity, band insulation, ferromagnetism, antiferromagnetism, and the quantum Hall states. The low energy excited quantum states of these systems are particles in exactly the same sense that the electron in the vacuum of quantum electrodynamics is a particle: Yet they are not elementary, and, as in the case of sound, simply do not exist outside the context of the stable state of matter in which they live. These quantum protectorates, with their associated emergent behavior, provide us with explicit demonstrations that the underlying microscopic theory can easily have no measurable consequences whatsoever at low energies. The nature of the underlying theory is unknowable until one raises the energy scale sufficiently to escape protection".

The notion of quantum protectorate was introduced to unify some generic features of complex physical systems on different energy scales, and is a complimentary unifying idea resembling in a certain sense the symmetry breaking concept, quasiaverages, and so on.. For example, the sources of quantum protection in high-T_c superconductivity and low-dimensional systems were discussed as well in their study. According to P.W. Anderson and D.Pines, the source of quantum protection is likely to be a collective state of the quantum field, in which the individual particles are sufficiently tightly coupled that elementary excitations no longer involve just a few particles, but are collective excitations of the whole system. As a result, macroscopic behavior is mostly determined by overall conservation laws.

In our interdisciplinary review [6] we analyzed the applications of the symmetry principles to quantum and statistical physics in connection with some other branches of science. The profound and innovative idea of quasiaverages formulated by N.N.Bogoliubov, gives the so-called macro-objectivation of the degeneracy in domain of quantum statistical mechanics, quantum field theory and in the quantum physics in general. We discussed also the complementary unifying ideas of modern physics, namely: spontaneous symmetry breaking, quantum protectorate and emergence. The interrelation of the concepts of symmetry breaking, quasiaverages and quantum protectorate was analyzed in the context of quantum theory and statistical physics. The main aim of that paper were to demonstrate the connection and interrelation of these conceptual advances of the many-body physics and to try

to show explicitly that those concepts, though different in details, have a certain common features. Many problems in the field of statistical physics of complex materials and systems (e.g. the chirality of molecules) and the foundation of the microscopic theory of magnetism [14,15] and superconductivity [15] were discussed in relation to these ideas. It is worth to emphasize once again that the notion of quantum protectorate complements the concepts of broken symmetry and quasiaverages by making emphasis on the hierarchy of the energy scales of many-particle systems. In an indirect way these aspects of hierarchical structure arose already when considering the scale invariance and spontaneous symmetry breaking in many problems of classical and quantum physics.

It was shown also in papers [6, 15, 16] that the concepts of symmetry breaking perturbations and quasiaverages play an important role in the theory of irreversible processes as well. The method of the construction of the nonequilibrium statistical operator [16] becomes especially deep and transparent when it is applied in the framework of the Bogoliubov's quasiaverage concept. For detailed discussion of the Bogoliubov's ideas and methods in the fields of nonlinear oscillations and nonequilibrium statistical mechanics see Refs. [15,16]. Thus, it was demonstrated in Ref. [6] that the connection and interrelation of the conceptual advances of the many-body physics discussed above show that those concepts, though different in details, have complementary character.

To summarize, the ideas of symmetry breaking, quasiaverages, emergence and quantum protectorate play constructive unifying role in modern theoretical physics. The main suggestion is that the emphasis of symmetry breaking concept is on the symmetry itself, whereas the method of quasiaverages emphasizes the degeneracy of a system. The idea of quantum protectorate reveals the essential difference in the behaviour of the complex many-body systems at the low-energy and high-energy scales. Thus the role of symmetry (and the breaking of symmetries) in combination with the degeneracy of the system was reanalyzed and essentially clarified within the framework of the method of quasiaverages. The complementary notion of quantum protectorate might provide distinctive signatures and good criteria for a hierarchy of energy scales and the appropriate emergent behavior. It was demonstrated also that the Bogoliubov's method of quasiaverages plays a fundamental role in equilibrium and nonequilibrium statistical mechanics and quantum field theory and is one of the pillars of modern physics.

We believe that all these concepts will serve for the future development of physics [17] as useful practical tools. Additional material and discussion of these problems can be found in recent publications [18, 19].

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